



# Charm Production at H1

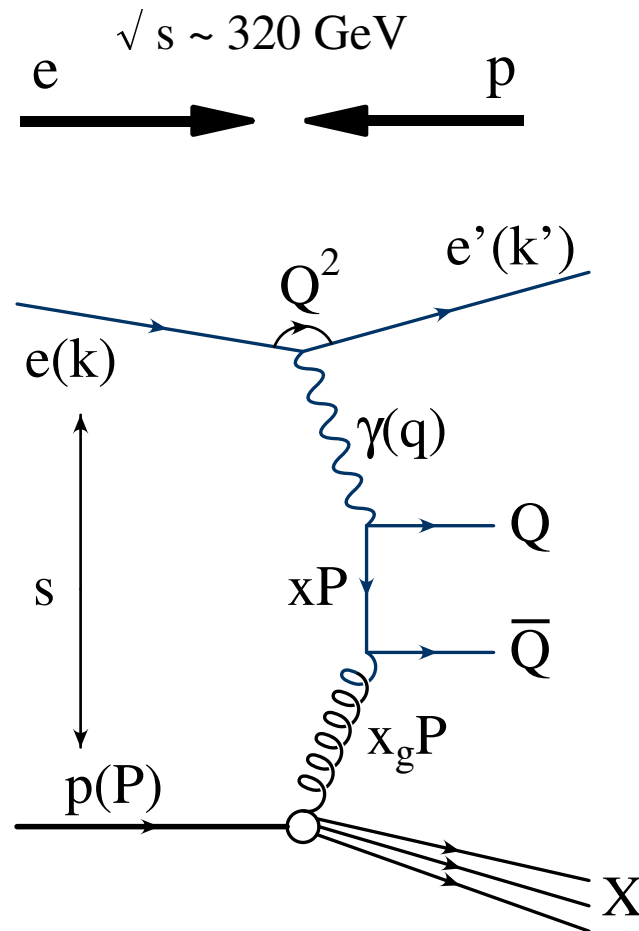


## Outline

- Introduction
- Charm Production in DIS
- Charm Photoproduction
- Double Tags
- Charm in Diffraction
- Summary and Outlook



# Heavy Quark Production Kinematics



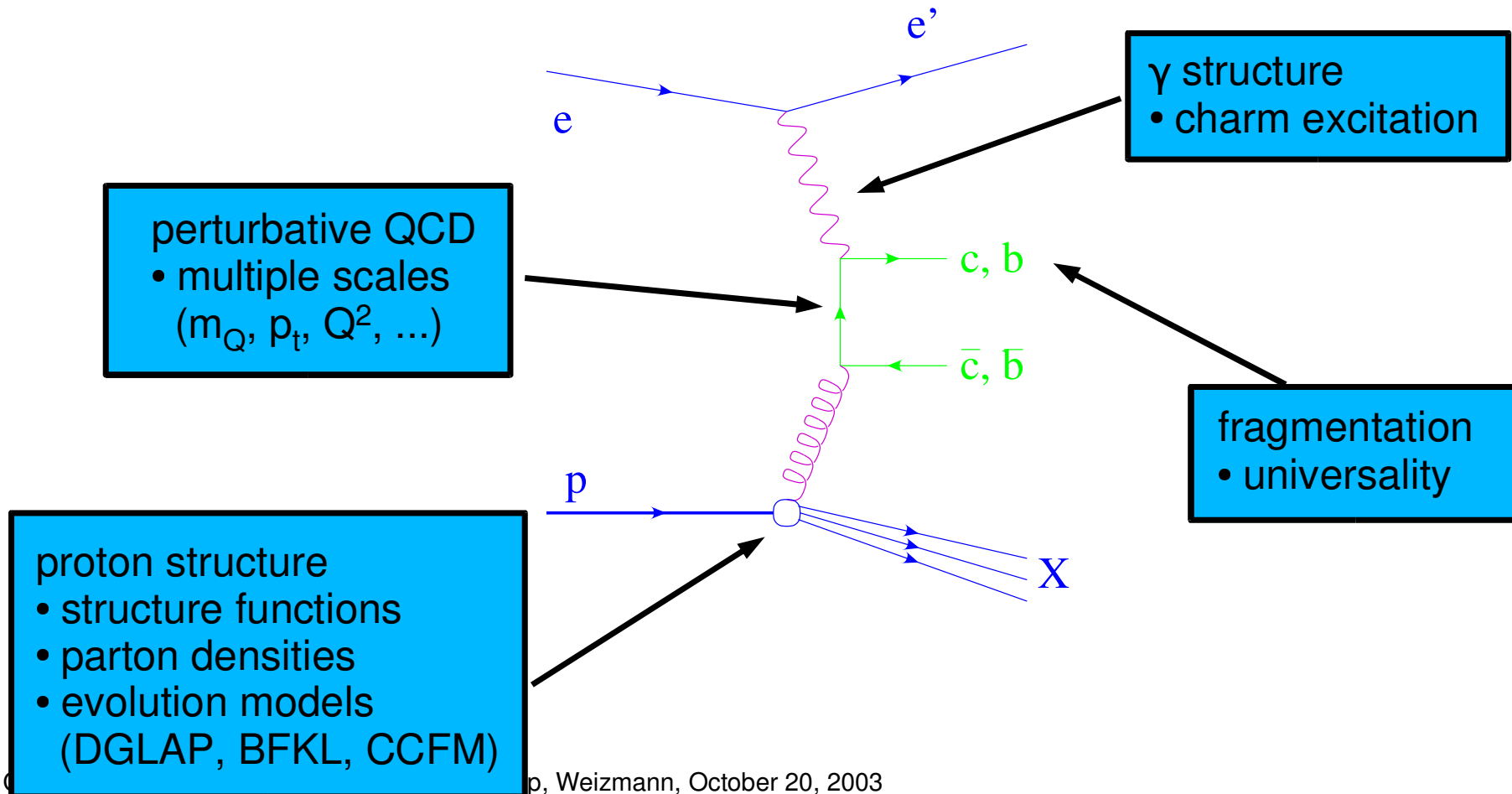
- two kinematical regions
  - photon almost on mass shell ( $Q^2 \rightarrow 0$ )
    - photoproduction (PHP)
  - photon highly virtual ( $Q^2 > 1 \text{ GeV}^2$ )
    - deep inelastic scattering (DIS)
- same production mechanism (photon gluon fusion) but real photons can behave as hadrons



# Heavy Quark Production Probing QCD



factorization:  $p$  structure  $\otimes$  pQCD  $\otimes$   $\gamma$  structure  $\otimes$  fragmentation





# Heavy Quark Production



- test perturbative QCD
- study structure of
  - proton (in particular gluon content)
  - photon
- study fragmentation, hadronization, ...

- cross sections at HERA are large

$$\sigma(e p \rightarrow c X) \sim O(1 \mu\text{b})$$

- but

- acceptance, trigger, ...

- visible cross sections are small

$$\sigma_{\text{vis}} \sim O(10 \text{ nb})$$

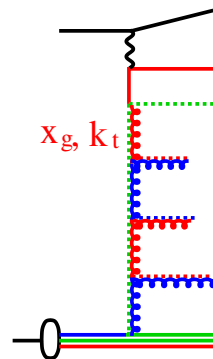


# Modelling Heavy Quark Production



- pQCD calculations in NLO (DGLAP evolution)
  - fixed (NLO) order (FO) calculations (“massive”)
    - HQ mostly via BGF (quark masses taken into account)
    - valid for  $Q, p_t \approx m_Q$
  - resummed (RS) calculations (“massless”)
    - HQ part of parton densities (massless quarks)
    - resum contributions of large logarithms ( $Q/m_Q, p_t/m_Q$ )
    - valid for  $Q, p_t \gg m_Q$
  - matched calculations (FONLL)
    - merge FO and RS calculations

- MC generators (LO matrix elements + parton showers)
  - AROMA: direct only, DGLAP evolution
  - HERWIG, PYTHIA, RAPGAP: direct + resolved, DGLAP
  - CASCADE: direct, CCFM like evolution
  - CCFM (wrt DGLAP)
    - no ordering in  $k_t$  required
    - gluon density and hard cross section  $k_t$  dependent
    - evolution phase space larger



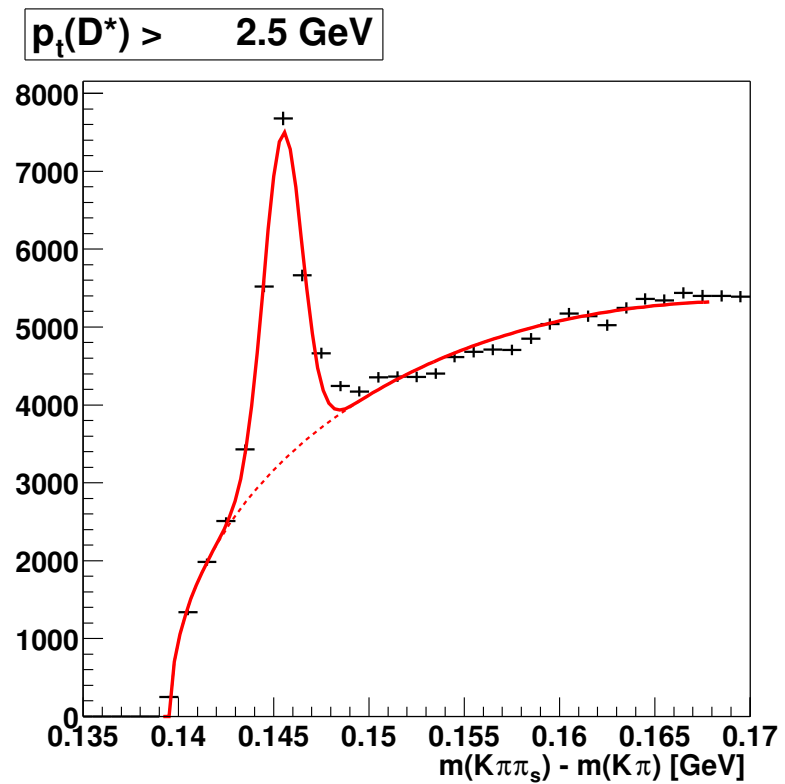
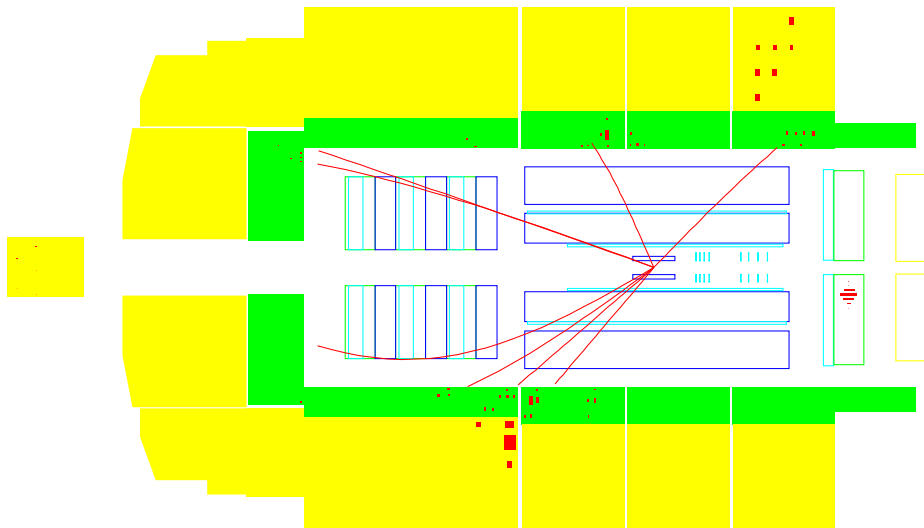


# Charm Tagging



- mass difference method,  
e.g.

$$\Delta M = M(K^-\pi^+\pi^+) - M(K^-\pi^+)$$

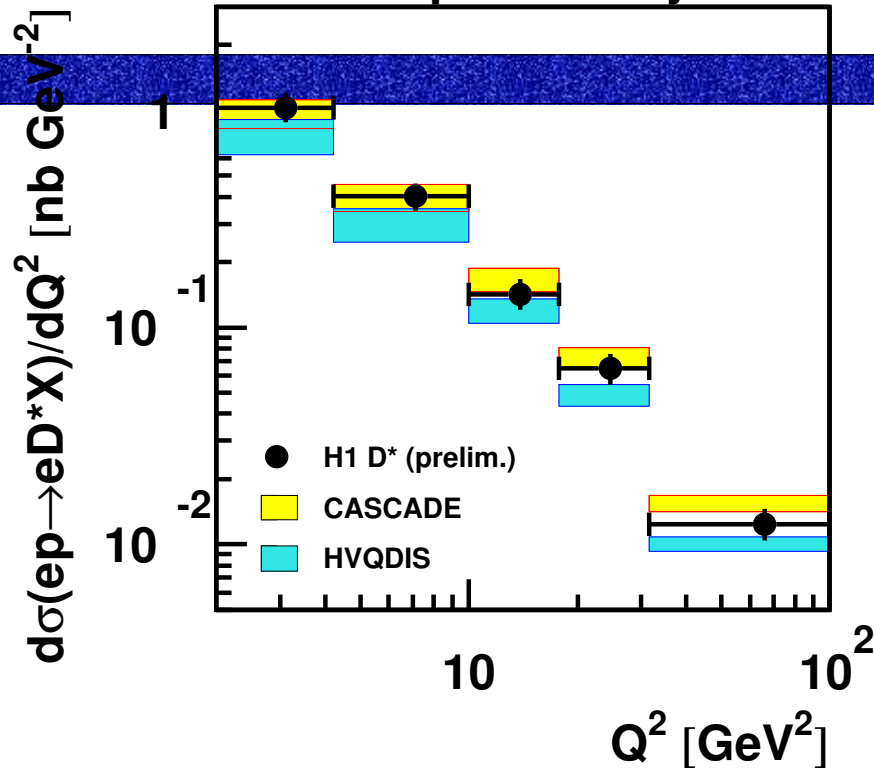




# Differential Cross Sections (DIS)

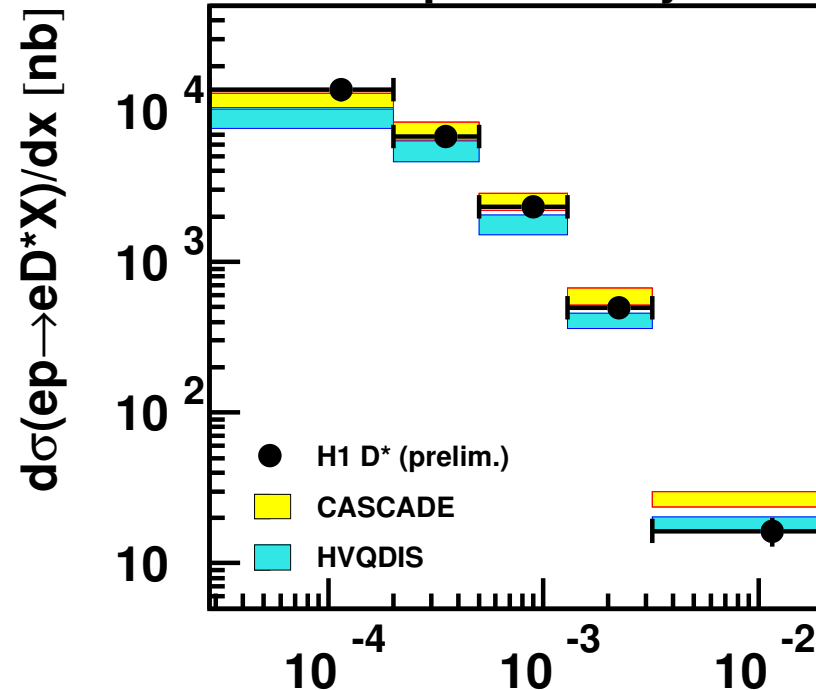


H1 preliminary



$2 < Q^2 < 100 \text{ GeV}^2$   
 $0.05 < y < 0.7$   
 $1.5 < p_t(D^*) < 15 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$

H1 preliminary



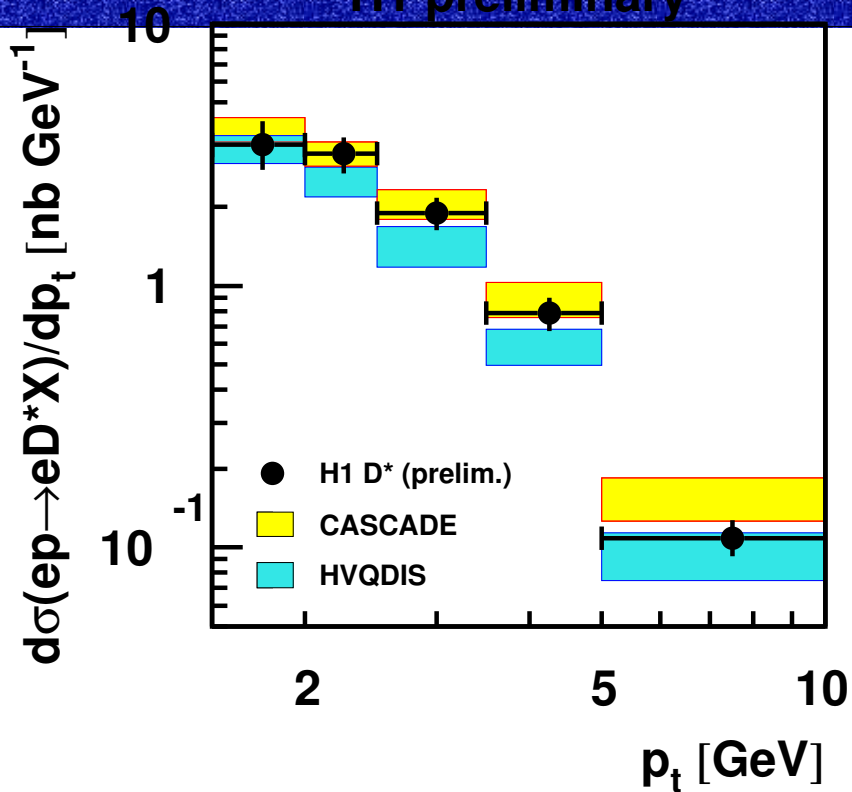
- theoretical uncertainties due to charm quark mass and fragmentation
- measured cross section larger than NLO calculation (HVQDIS), shape okay
- measured cross section agrees better with CCFM model (CASCADE)



# Differential Cross sections (DIS)

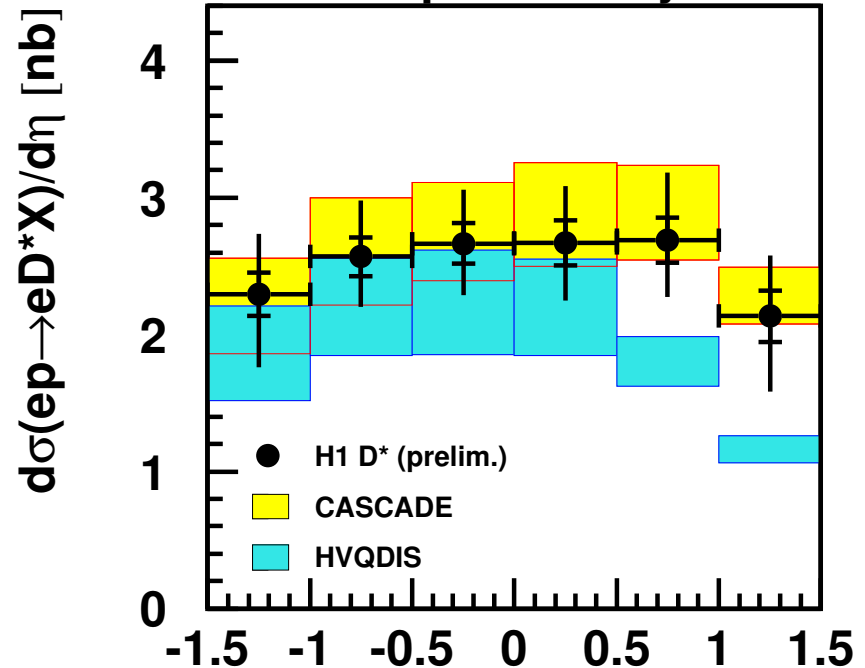


H1 preliminary



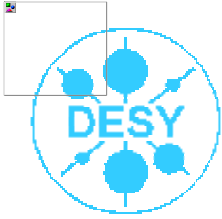
$2 < Q^2 < 100 \text{ GeV}^2$   
 $0.05 < y < 0.7$   
 $1.5 < p_t(D^*) < 15 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$

H1 preliminary



- HVQDIS: reasonable agreement, except in forward region
- CASCADE: better agreement with data

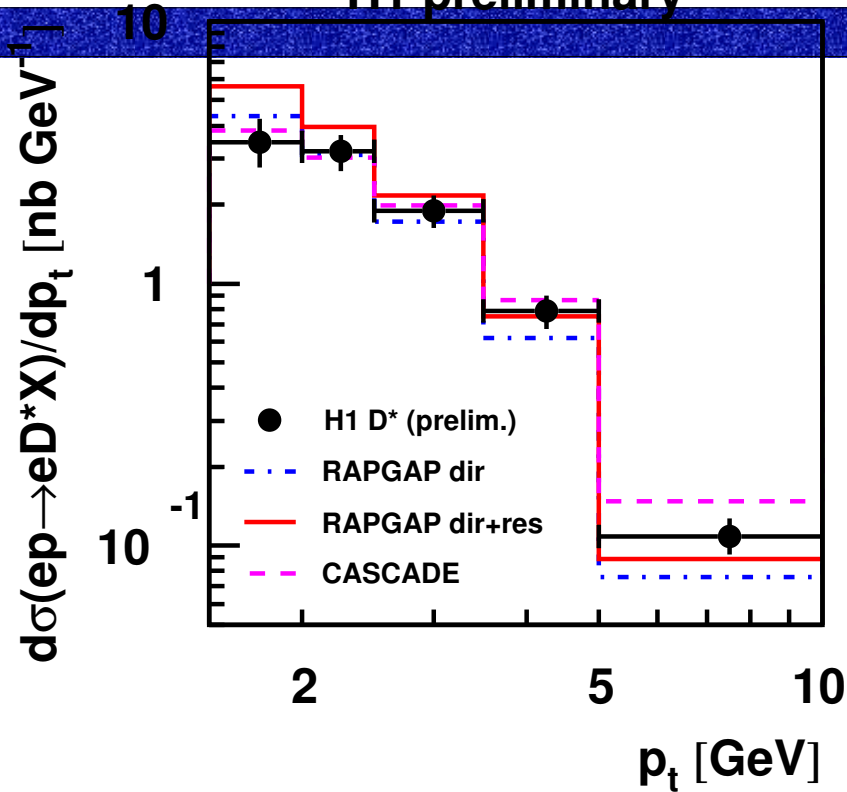




# Differential Cross sections (DIS)



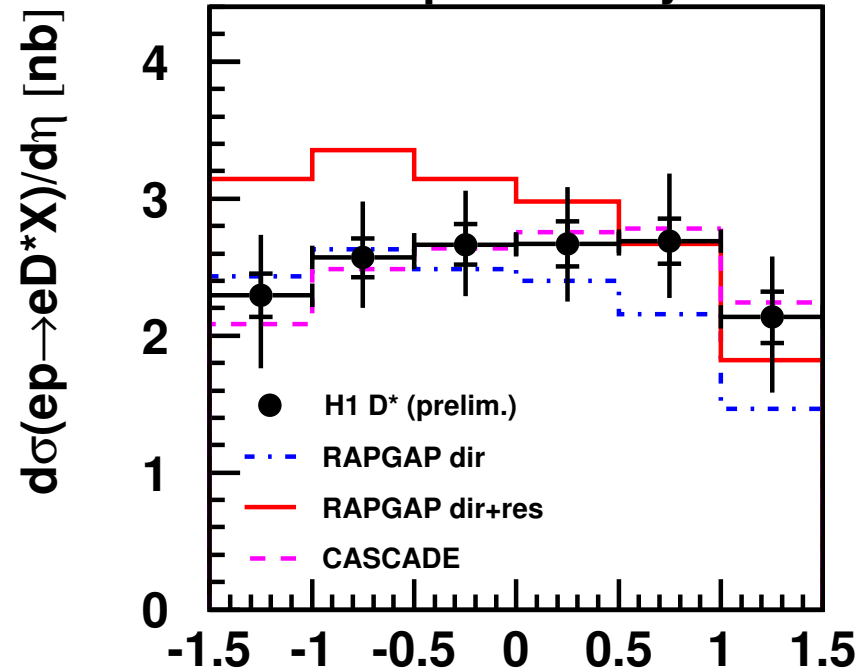
H1 preliminary



- RAPGAP with direct processes only slightly below data
- RAPGAP with resolved contribution taken into account considerably above data

$2 < Q^2 < 100 \text{ GeV}^2$   
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 $1.5 < p_t(D^*) < 15 \text{ GeV}$   
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H1 preliminary

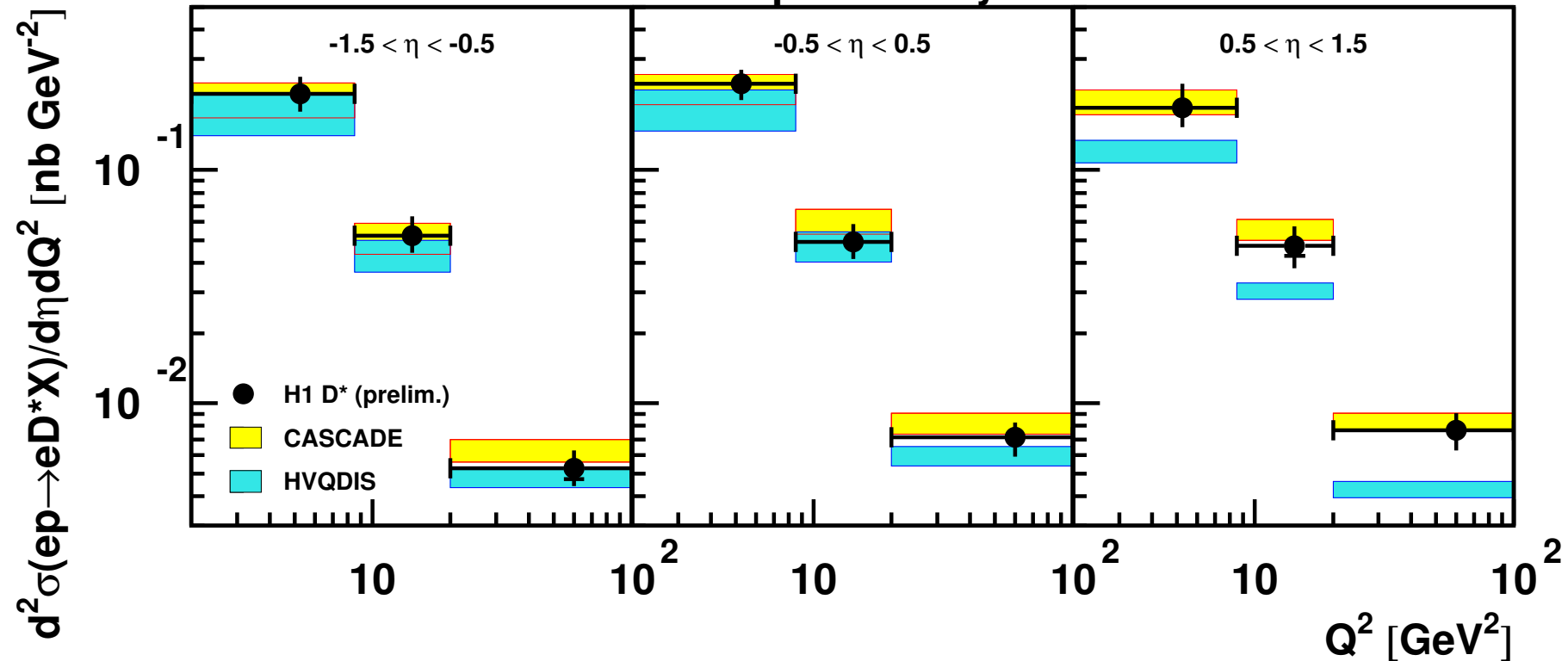




# Double Differential Cross sections (DIS)

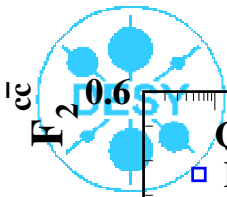


H1 preliminary



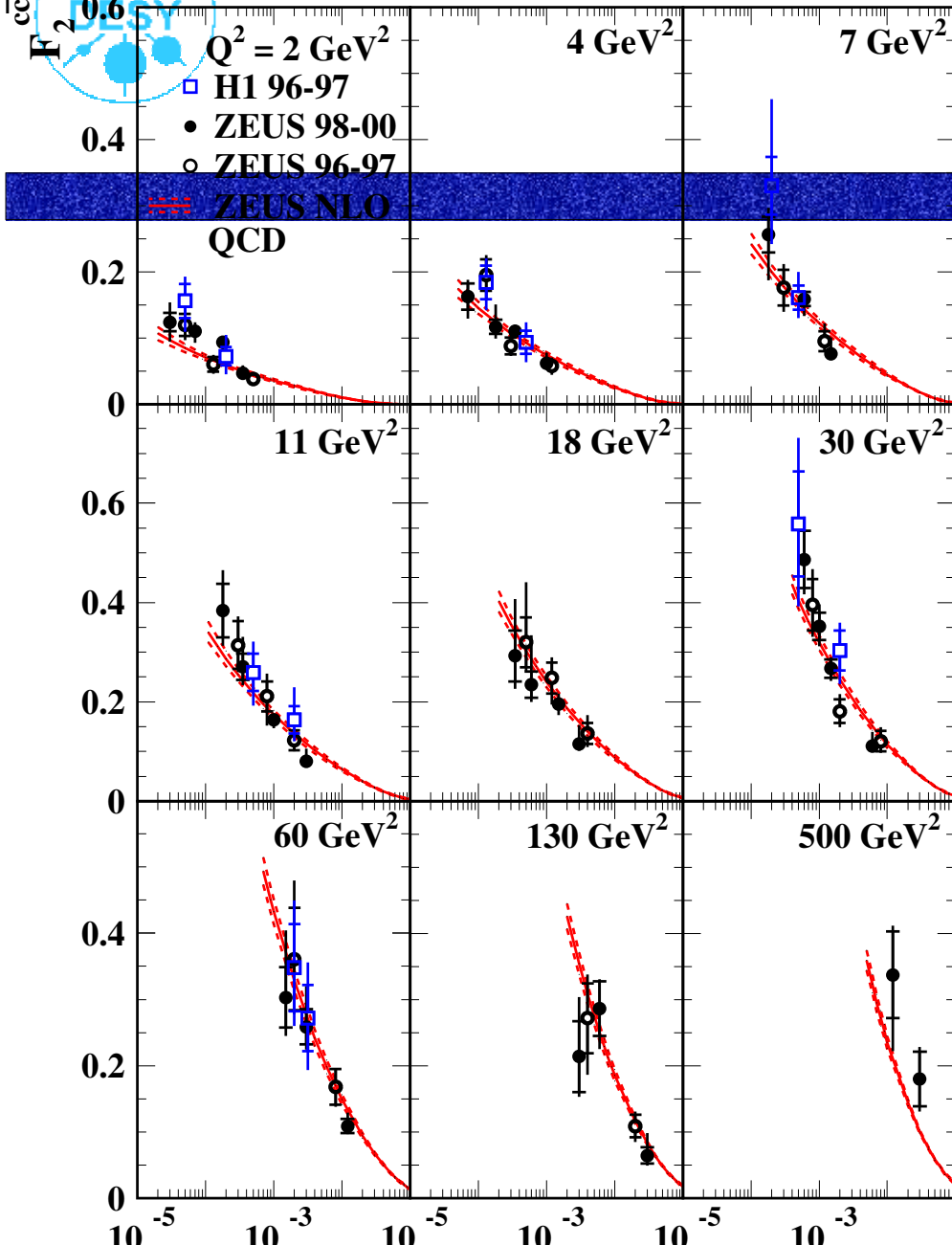
$2 < Q^2 < 100 \text{ GeV}^2$   
 $0.05 < y < 0.7$   
 $1.5 < p_t(D^*) < 15 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$

- HVQDIS: excess independent of  $Q^2$  and concentrated on low  $p_T$
- CASCADE: reasonable agreement with data



# HERA $F_2^{c\bar{c}}$

$F_2^c$



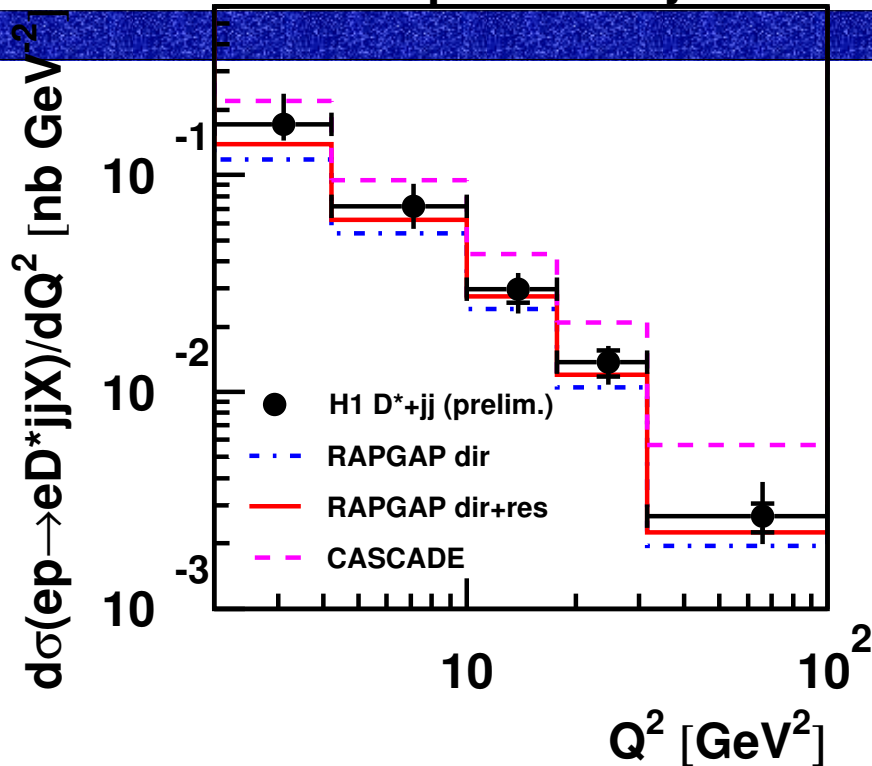
- measure  $D^*$  cross section in restricted kinematic range
  - model dependent extrapolation
- agreement between H1 and ZEUS measurements
- agreement with ZEUS NLO QCD fit over wide range in  $Q^2$  and  $x$
- prediction of charm contribution to  $F_2$  from scaling violations consistent with  $F_2^c$  measurement



# D\* + Jets (DIS)



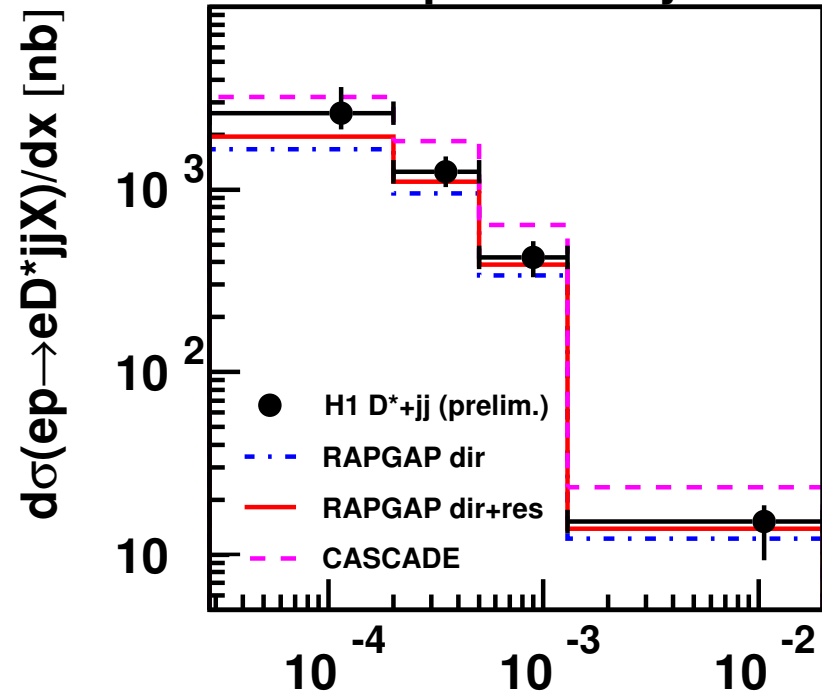
H1 preliminary



- CASCADE above data (different from inclusive D\* measurement)
- direct RAPGAP below data
- direct + resolved RAPGAP closer to data

$2 < Q^2 < 100 \text{ GeV}^2$   
 $0.05 < y < 0.7$   
 $1.5 < p_t(D^*) < 15 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$   
 $E_t(\text{jet1}) > 4 \text{ GeV}$   
 $E_t(\text{jet2}) > 3 \text{ GeV}$   
 $-1 < \eta(\text{jet1,2}) < 2.5$

H1 preliminary

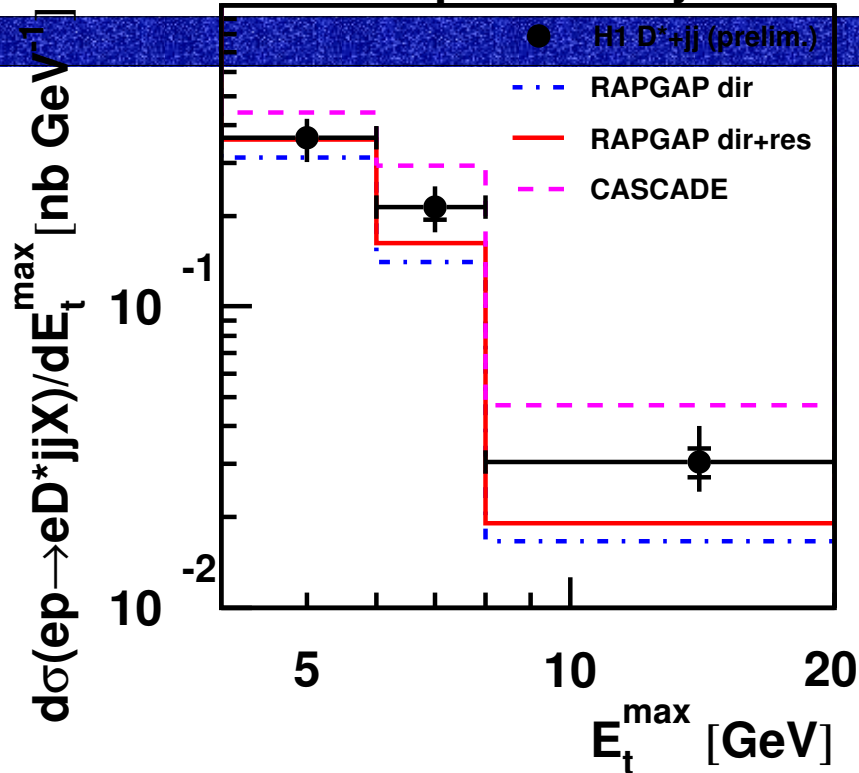




# D\* + Jets (DIS)



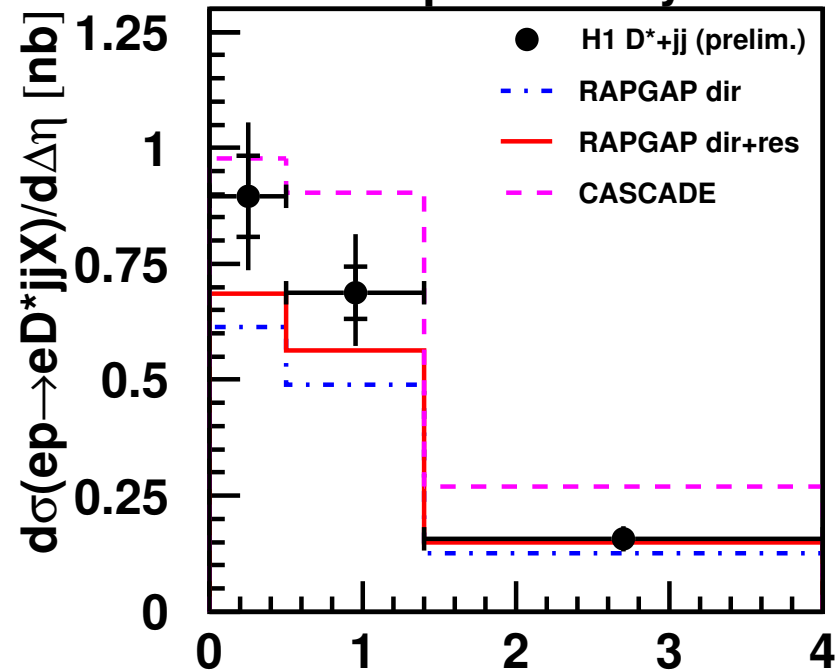
H1 preliminary



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- CASCADE above data (different from inclusive D\* measurement)
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H1 preliminary



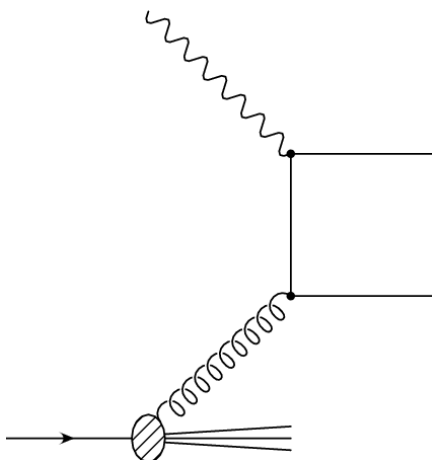


# Charm Photoproduction

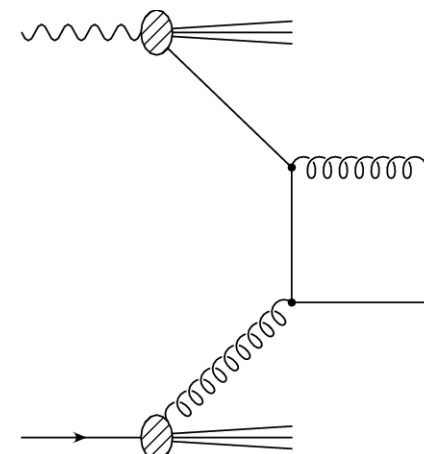
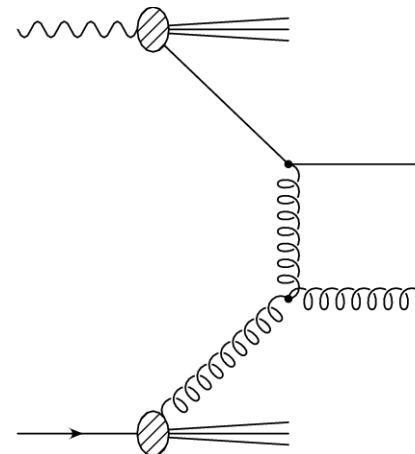


- quasi-real photons exhibit hadronic behaviour

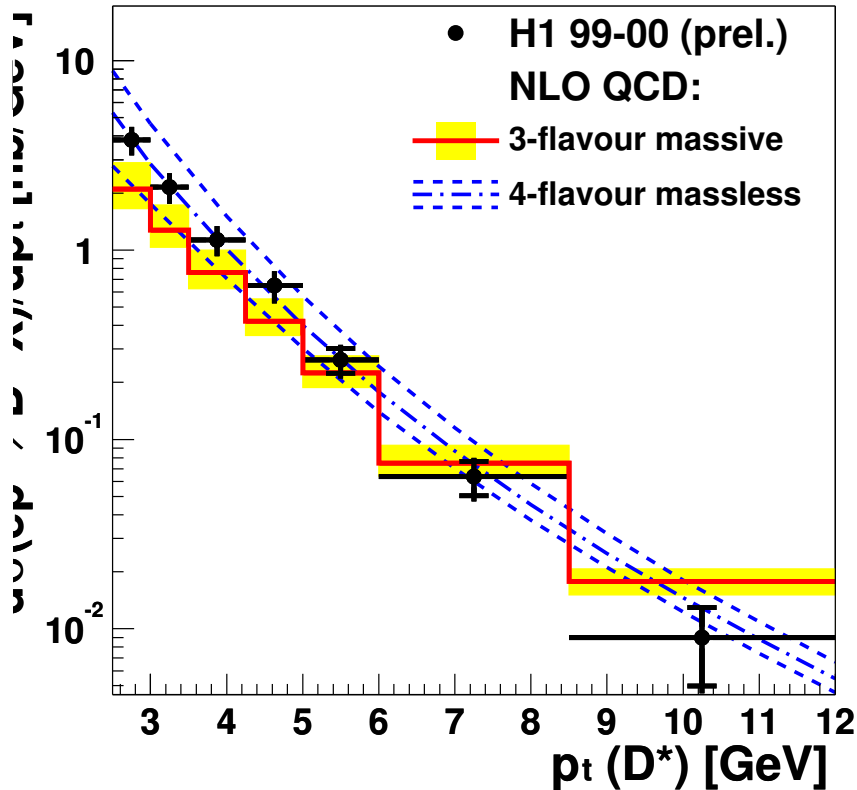
direct



charm excitation

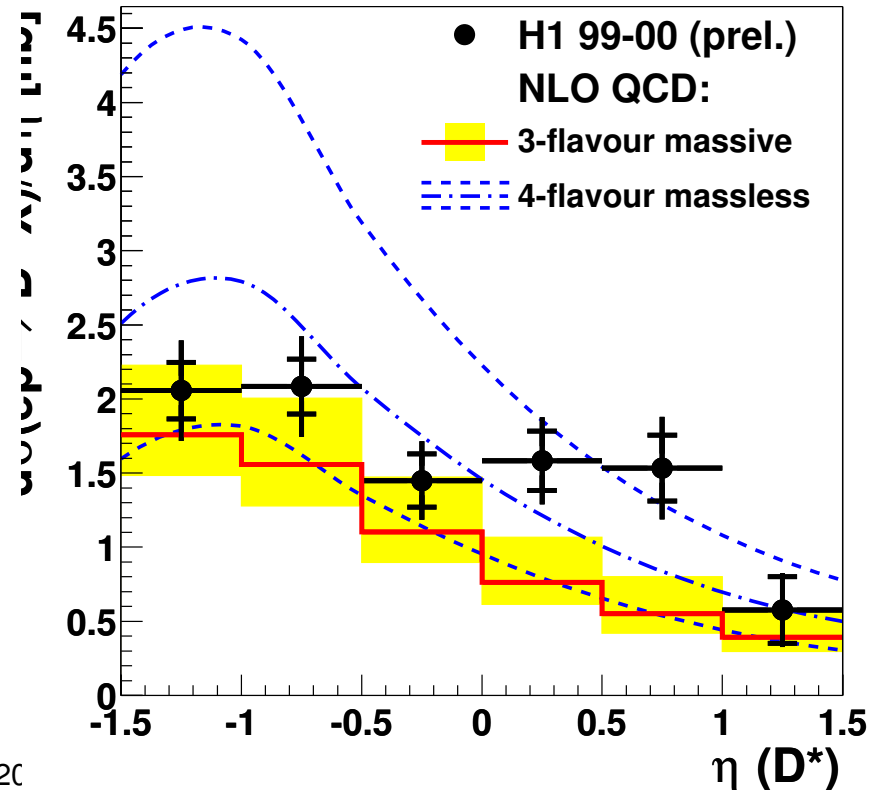


# Differential Cross sections (PHP)



$Q^2 < 0.01 \text{ GeV}^2$   
 $171 < W < 256 \text{ GeV}$   
 $p_t(D^*) > 2.5 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$

- theoretical uncertainties due renormalization and factorization scales
- “3 flavour massive” below data (at low  $p_t$ )
- “4 flavour massless” reasonable agreement
- enhancement in forward region

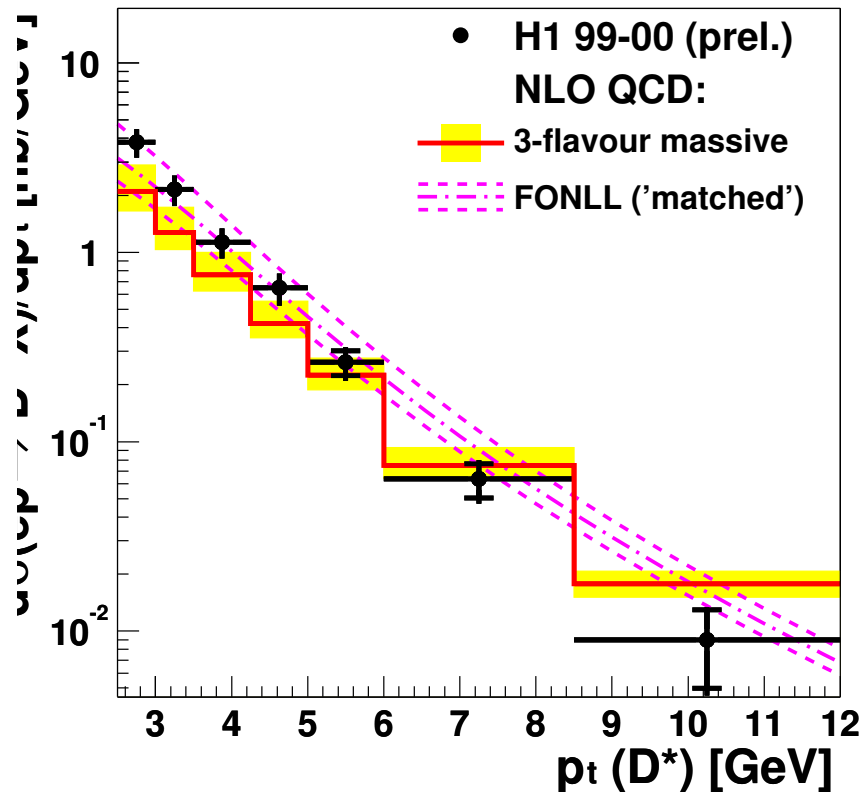




# Differential Cross sections (PHP)



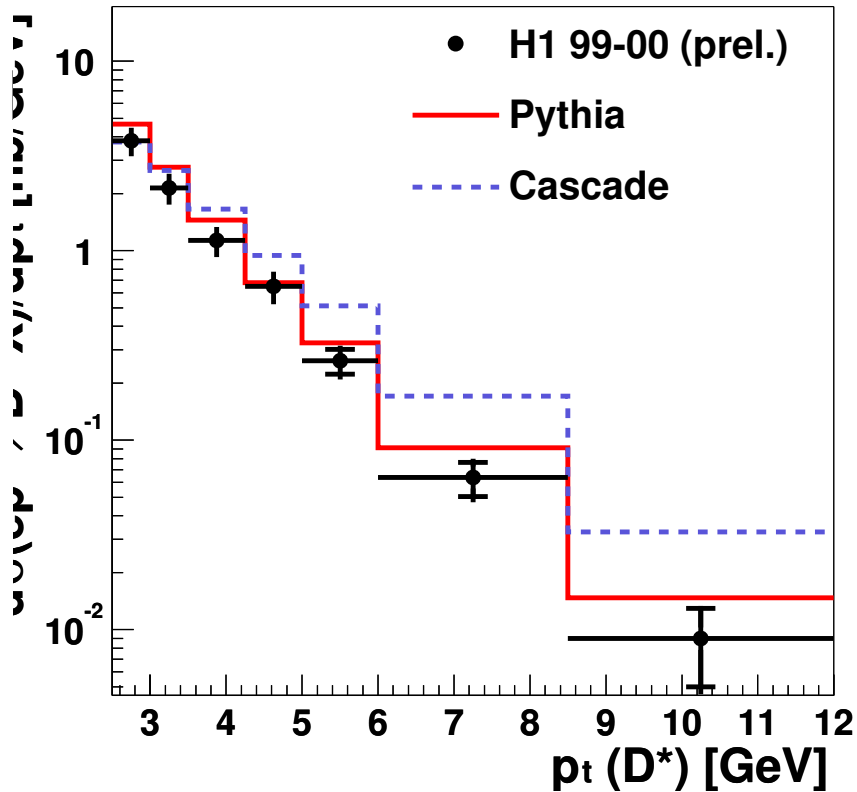
$Q^2 < 0.01 \text{ GeV}^2$   
 $171 < W < 256 \text{ GeV}$   
 $p_t(D^*) > 2.5 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$



- comparison with FONLL
  - dotted curve: central prediction
  - solid curve: all uncertainties added linearly
  - dashed curve: without factorization scale uncertainties
- FONLL closer to data in low  $p_t$  region than “3 flavour massive”

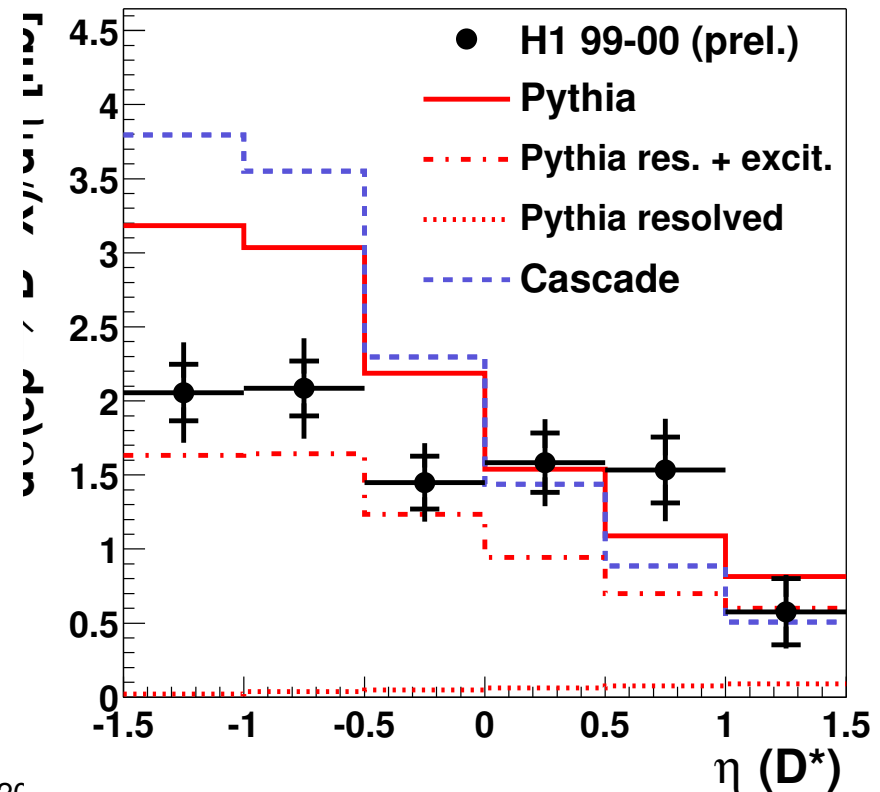


# Differential Cross sections (PHP)



- PYTHIA: slightly above data,  $p_t$  distribution okay, charm excitation important
- CASCADE:  $p_t$  distribution too hard
- both MC models cannot describe  $\eta$  distribution

$Q^2 < 0.01 \text{ GeV}^2$   
 $171 < W < 256 \text{ GeV}$   
 $p_t(D^*) > 2.5 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$

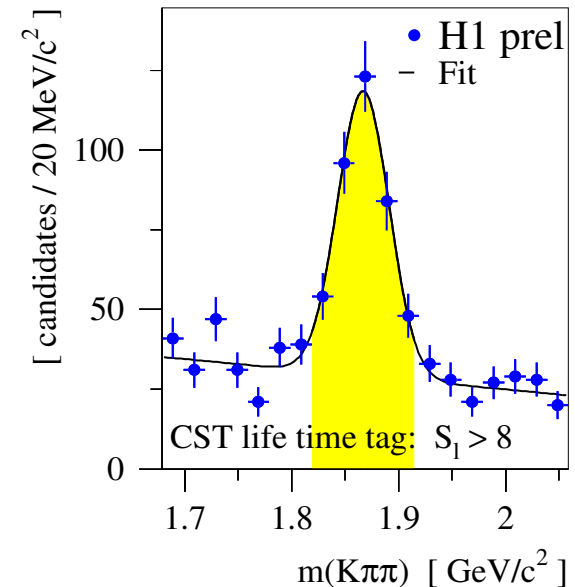
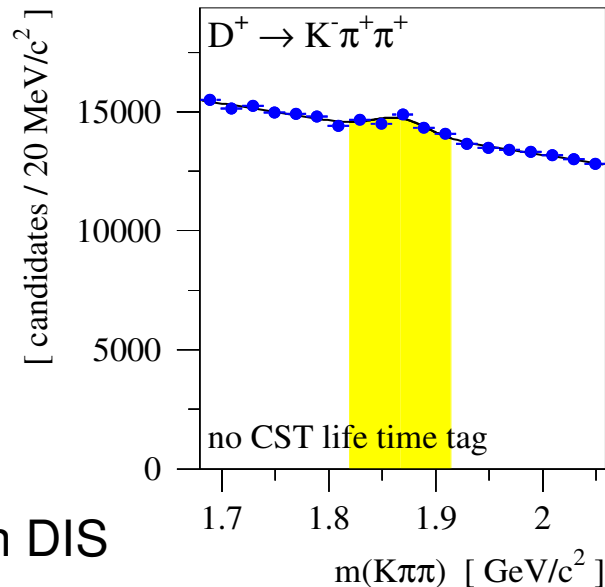
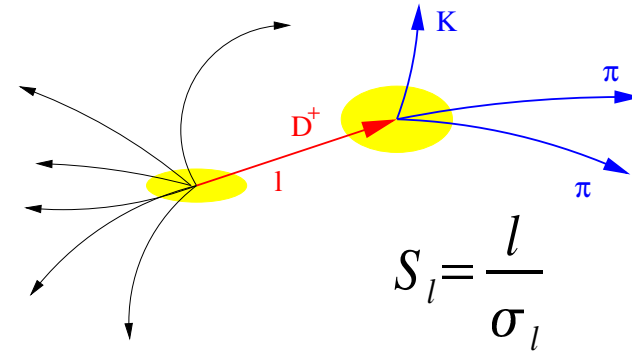




# Charm Tagging revisited



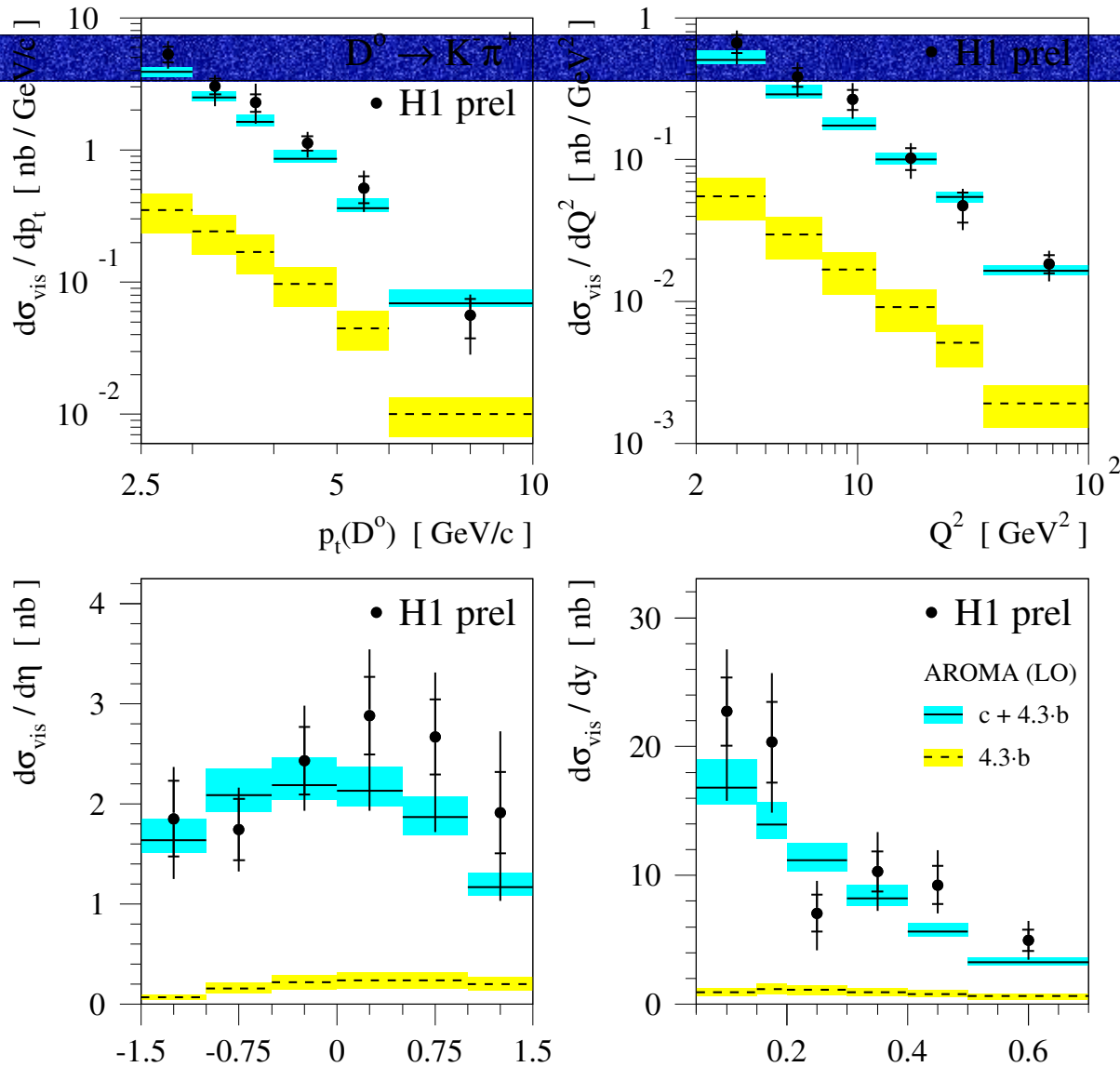
- vertex tagging (silicon vertex detector)
- study production of various charm hadrons ( $D^{*+}$ ,  $D^+$ ,  $D^0$ ,  $D_s^+$ ,  $(\Lambda_c)$ )
  - independent cross section measurements
  - fragmentation fractions



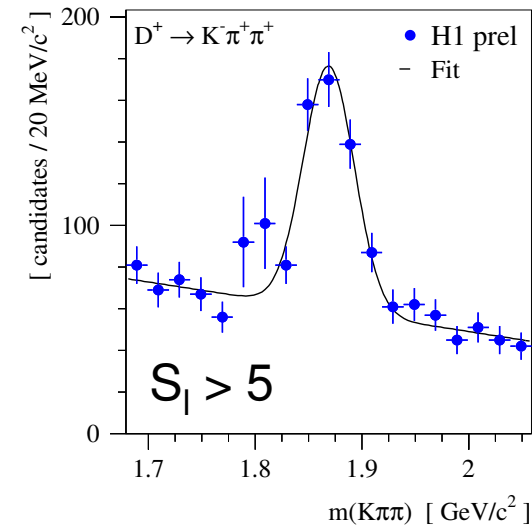
... an example:  $D^+$  production in DIS



# D<sup>+</sup> Production (DIS)



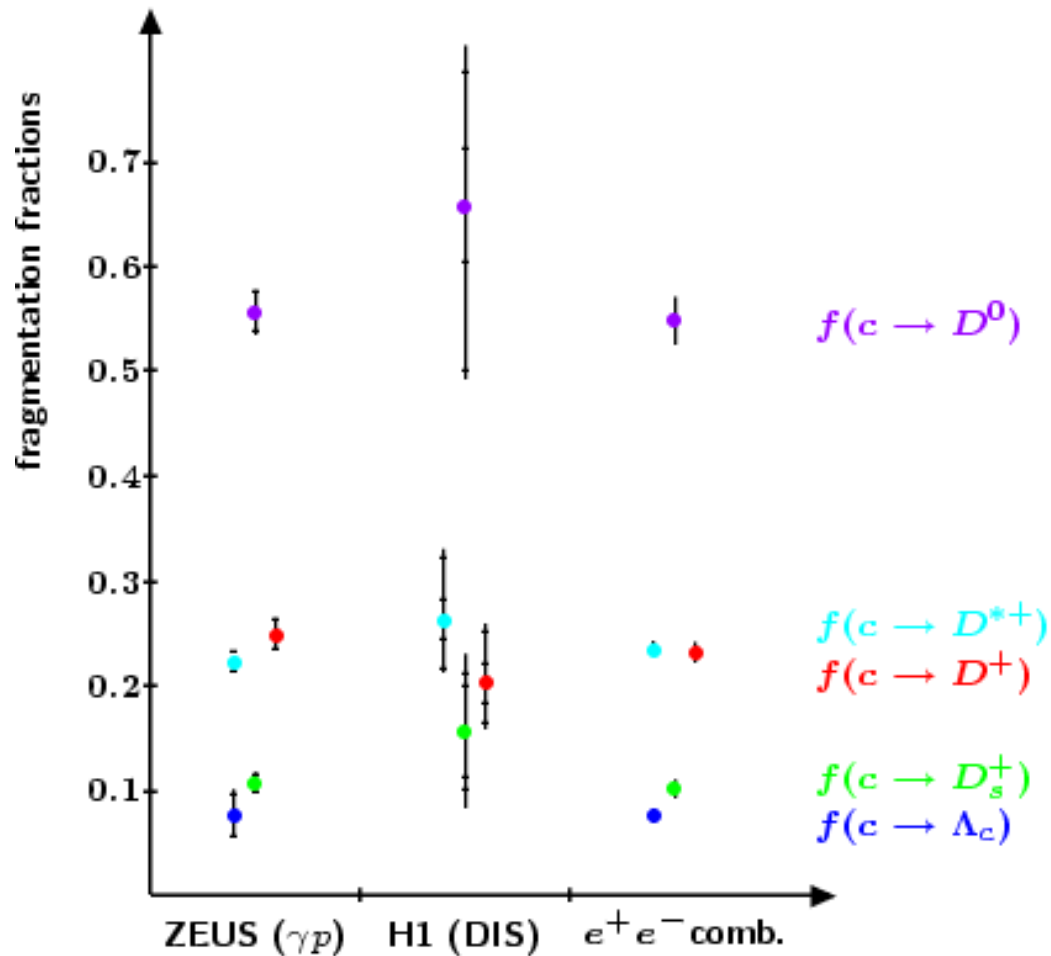
$2 < Q^2 < 100 \text{ GeV}^2$   
 $0.05 < y < 0.7$   
 $p_t(D^+) > 2.5 \text{ GeV}$   
 $|\eta(D^+)| < 1.5$



- good agreement with LO + PS prediction (AROMA) both in shape and magnitude
- similar for  $D^0, D_s$



# Fragmentation Ratios



- reconstruct all charm states
- consistent with measurements in  $e^+e^-$ , ..

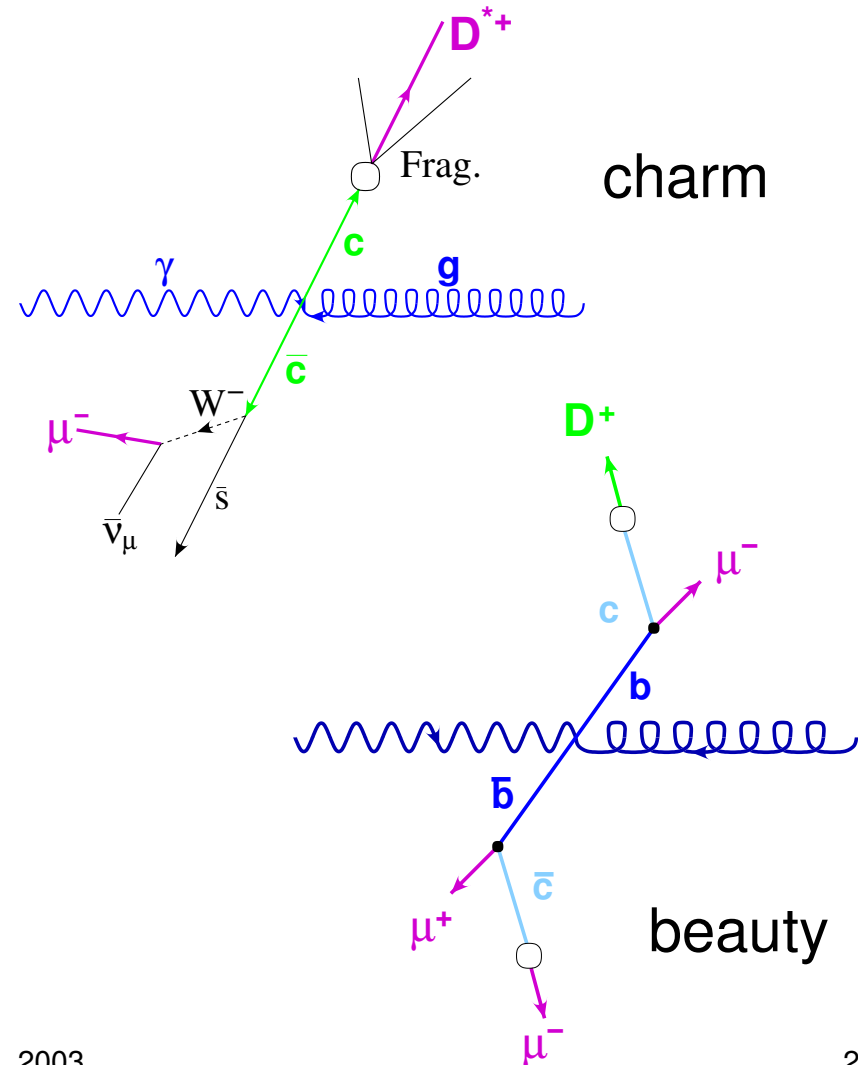
⇒ consistent with charm fragmentation universality



# Double Tags

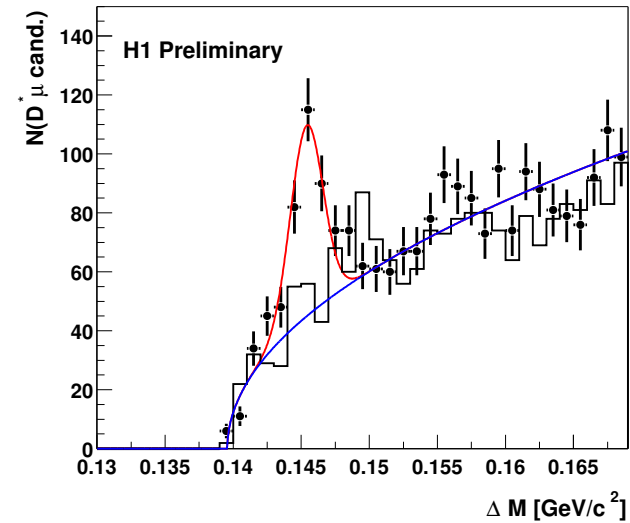
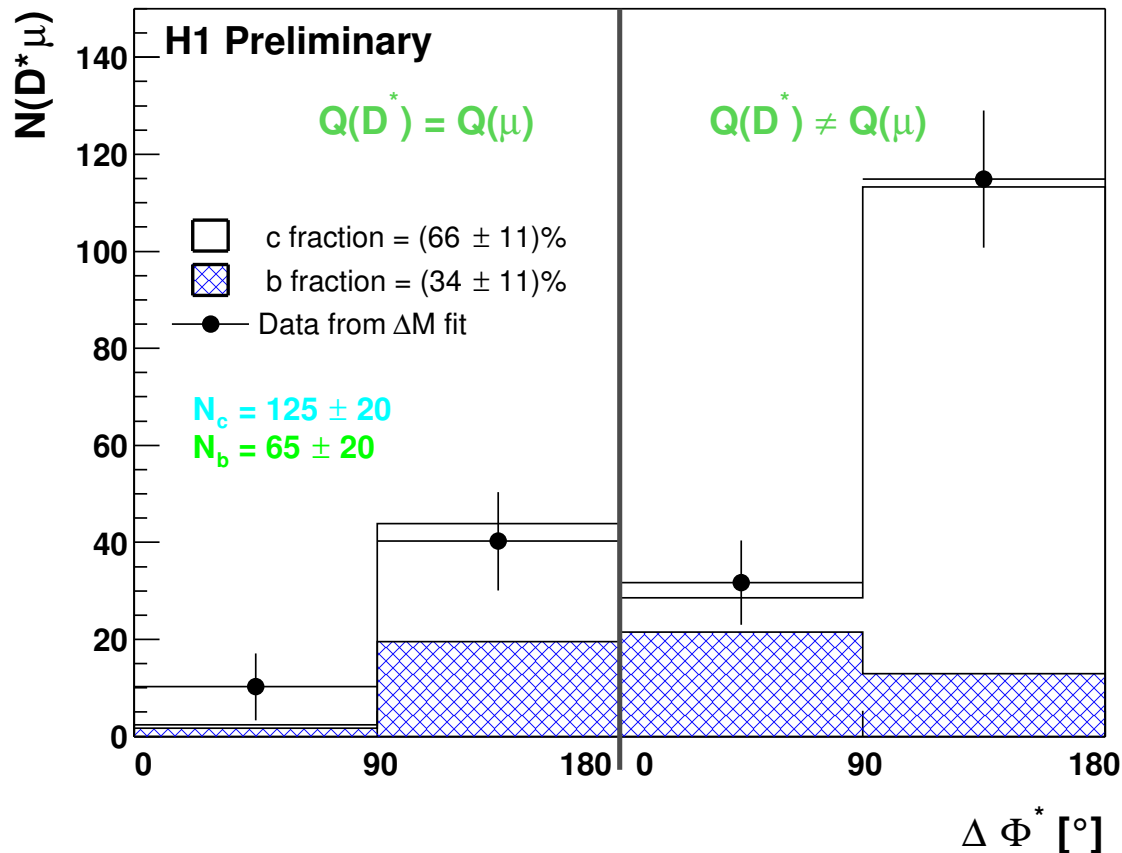


- tag both charm (beauty) quarks to completely reconstruct the hadronic final state, e.g.
  - $D^{*\pm} l^{\mp}$ ,  $D^{*+} D^{*-}$ ,  $l^+ l^-$ ,  $l = e, \mu$
  - measurement of the gluon density
  - sensitivity to higher orders and non-perturbative effects
- example:  $D^{*\pm} \mu^{\mp}$  analysis
  - exploit charge and angular correlations to separate charm and beauty
  - LO:
    - $\Delta\Phi = \pi$
    - $\Sigma p_t = 0$
    - $\Sigma Q = 0$
  - smearing due to higher orders and fragmentation





# D\*μ Double Tags

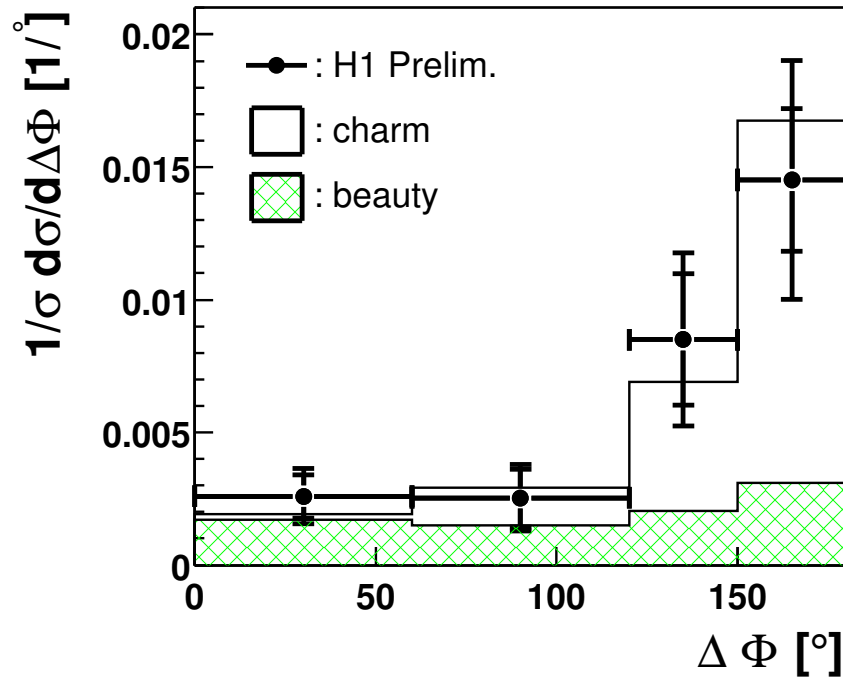


- measurement of total cross sections compatible with previous results

$p_t(D^*) > 2.5 \text{ GeV}$   
 $|\eta(D^*)| < 1.5$   
 $p_t(\mu) > 1. \text{ GeV}$   
 $|\eta(\mu)| < 1.74$   
 $0.05 < y < 0.7$

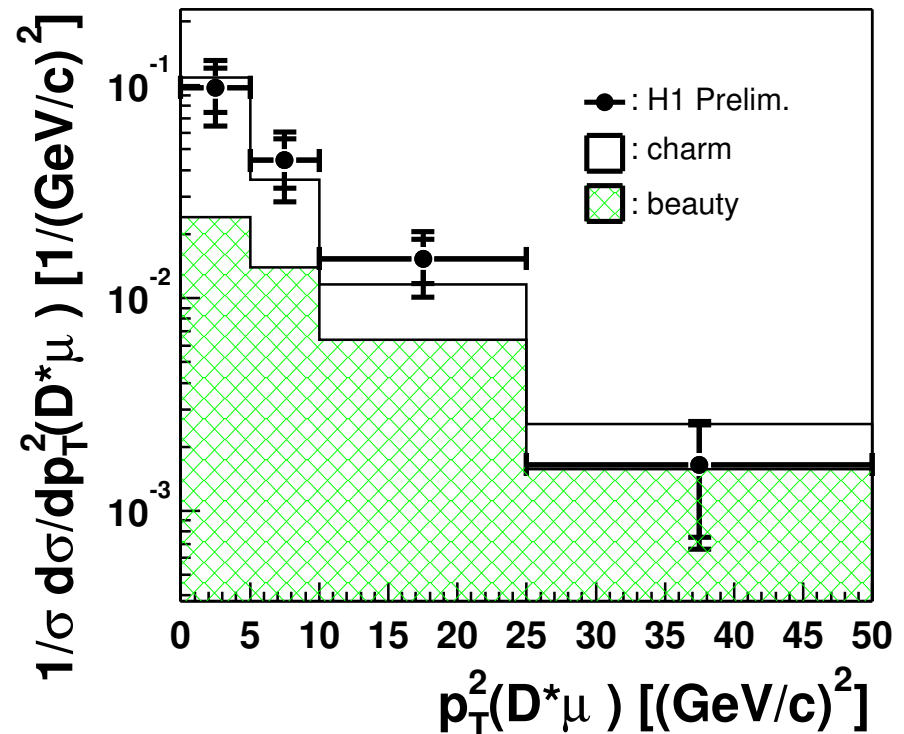


# D\*μ Double Tags



$p_t(D^*) > 2.5$  GeV  
 $|\eta(D^*)| < 1.5$   
 $p_t(\mu) > 1.$  GeV  
 $|\eta(\mu)| < 1.74$   
 $0.05 < y < 0.7$

- good agreement with LO+PS prediction
- large potential for HERA II

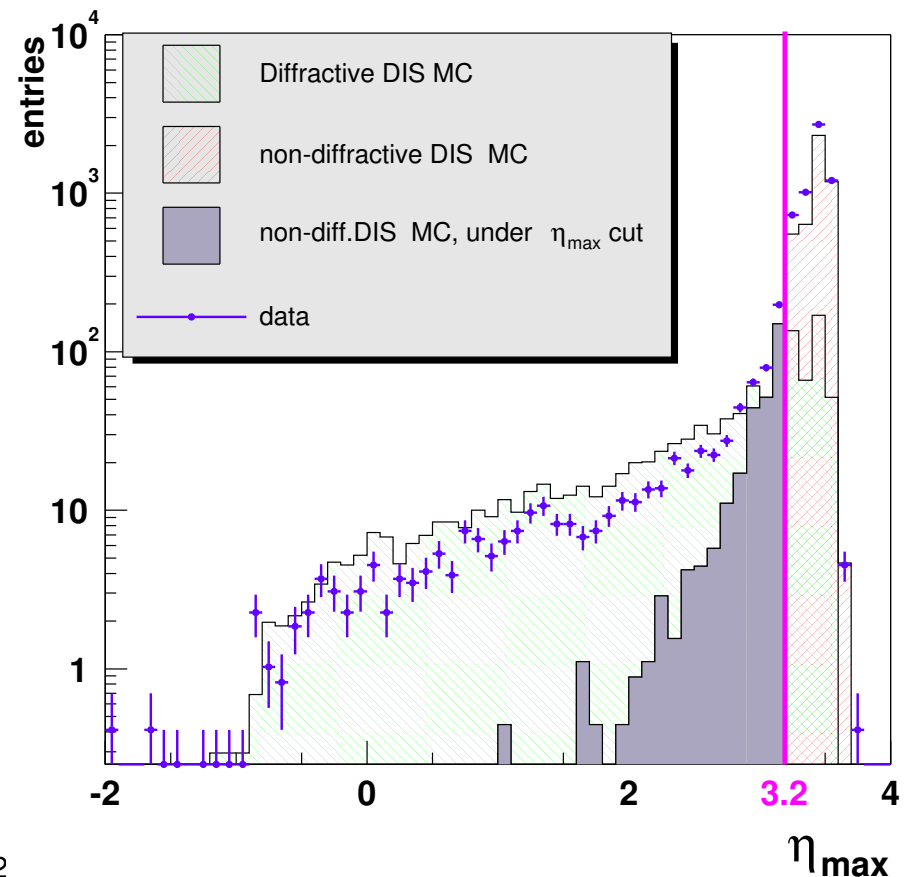
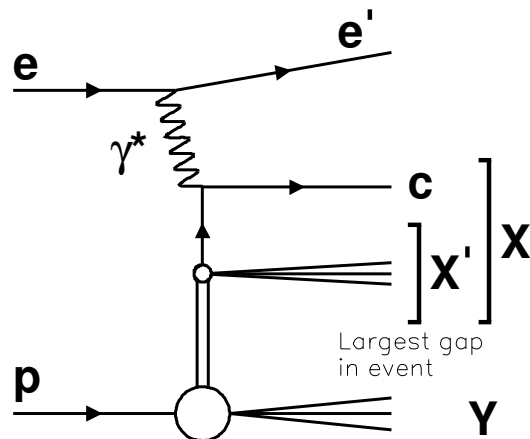




# Charm in Diffraction

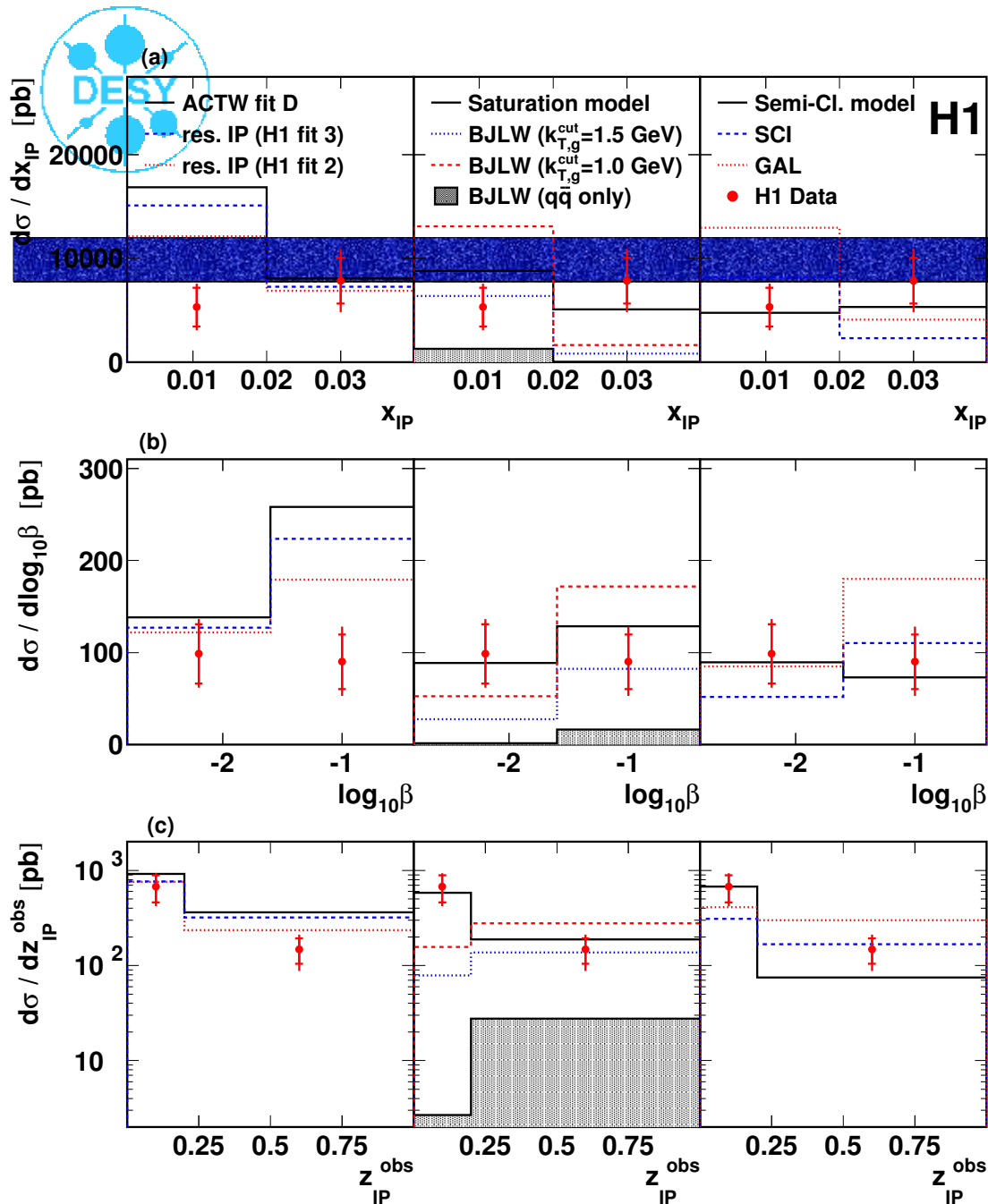


- rapidity gap events
  - attributed to diffractive or pomeron exchange
- investigate partonic nature of diffraction, using the photon as a probe
- production of open charm sensitive to gluon content
- test perturbative QCD based models of diffraction





# Charm in Diffraction



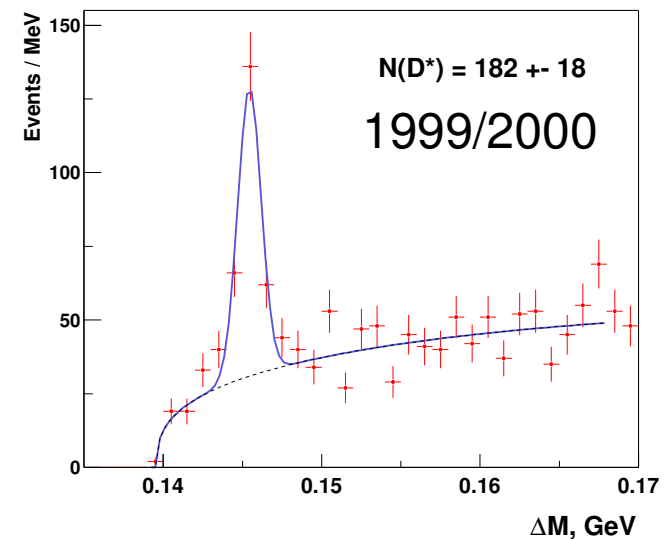
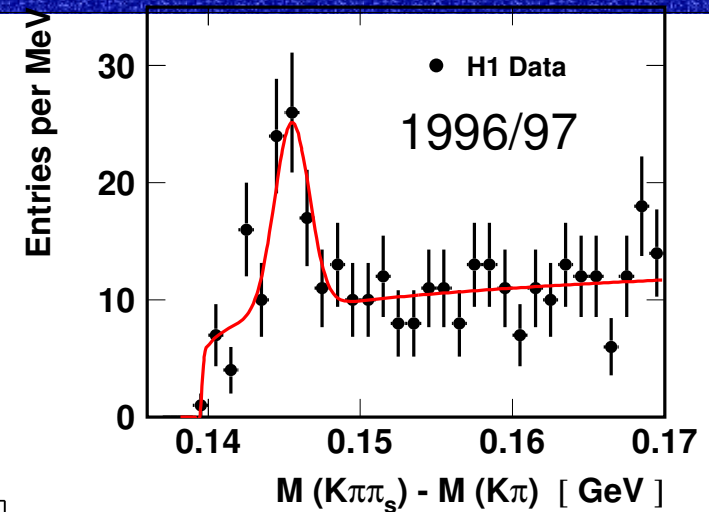
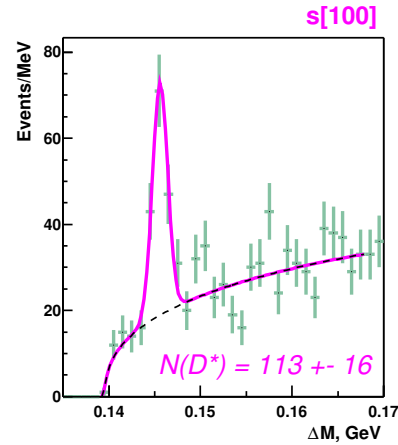
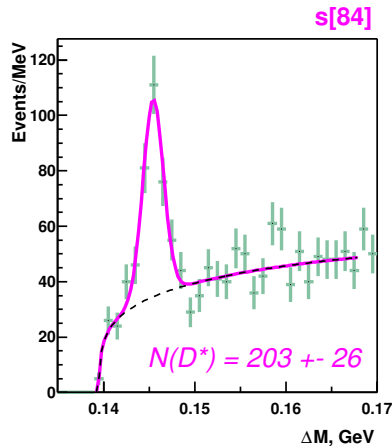
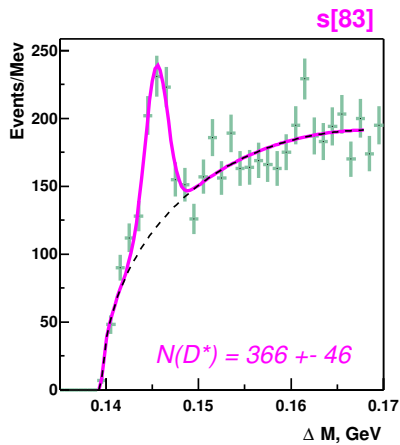
- 60% of charm production at low  $z_{IP} < 0.2$ , where BGF contribution is expected to dominate
- discrepancy between resolved pomeron model and data at low  $x_{IP}$ , high  $\beta$ , low  $z_{IP}$
- fair description of data by two gluon exchange models (BJLW)
- good description of data by saturation model
- good description by semi-classical model
- satisfactory description by soft colour neutralization models



# Charm in Diffraction short term prospects



- full HERA I dataset
  - factor 4 in statistics in DIS
  - plus photoproduction and low  $Q^2$  analyses





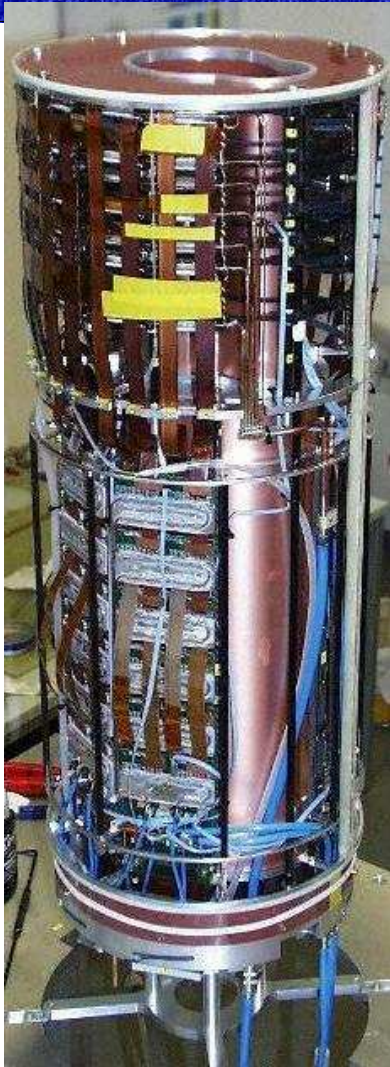
# Summary HERA I



- experimental problems
  - measurement in forward (proton) direction
  - triggering charm (low  $E_t$  processes in general)
- theoretical problems
  - theory uncertainties larger than measurement errors
- statistics limited at HERA I
  - double tags (e.g.  $D^*\mu$  analysis)
  - charm in diffraction (e.g. 250 events in DIS)
- Charm program at HERA I not exhausted yet
- not covered at HERA I
  - charm in charged current interactions (e.g. determine s quark density)
  
- H1 upgrade projects address these questions ...
- ... and of course a factor ( $>4$ ) in luminosity will play an important role



# H1 @ HERA II



- new detectors
  - FST
  - FTD
  - CIP
  - FTT (Fast Track Trigger)
  - ...
- will all help the charm programme





# Conclusions and Outlook



- HERA I has made (and will still to make) substantial contributions to
  - understand the production of charm (and beauty)
  - improve our knowledge about the structure of the proton and the photon
- Uncertainties of theoretical predictions are still very large
  - more precise calculations are very desirable (NNLO, NLO MC, ...)
- Experimental uncertainties typically smaller but still large
- HERA II with its considerable increase in luminosity and the improved H1 detector will allow even deeper insight into these interesting topics of QCD



## ... and finally



- bright future for Heavy Flavour Physics at HERA
  - improved detectors will allow to access new kinematical regions
  - increased statistics will allow more precise measurements
- a lot of interesting Heavy Flavour Physics can be expected in near future!